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Mechanical Properties of Centrifugally Cast Metal Matrix Composites

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OBJECTIVE

Determine the tensile and compressive mechanical properties for two metal matrix composite (MMC) aluminum cylinders manufactured through use of the centrifugal casting process.

RESULTS

Tensile specimens had very low elongations, typically less than 1% for the 10-volume-% alloy and less than 0.5% for the 20-volume-% alloy, although they did demonstrate some degree of plasticity. All tensile fractures exhibited at least one prominent dark inclusion. The proportional limit of the materials, measured in both tension and compression, was also quite low.

However, compressively strain hardening the cast MMC material by only 1% achieved impressive mechanical properties for an underwater hull material. Compressively strain-hardened MMCs were demonstrated to attain a **compressive yield strength greater than 80 ksi**, a modulus **greater than 20 x 10^6 psi up to 60 ksi**, and **greater than 18 x 10^6 psi up to 70 ksi**.

RECOMMENDATIONS

Further investigation should be pursued into the strain hardening of centrifugally cast cylinders for underwater hull materials. A more detailed study of strain-hardened mechanical properties should be conducted to include an evaluation of the material's fracture toughness and fatigue characteristics.

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INTRODUCTION

Tensile and compressive mechanical properties were determined for two metal matrix composite (MMC) aluminum cylinders manufactured by Westinghouse STC, Advanced Materials Department, Pittsburgh, PA (Gungor, 1990) through use of a centrifugal casting process. The composite material used was SiC particle reinforced A356 Al alloy, originally procured from Dural Aluminum Composites Corporation, San Diego, CA. One cylinder was made from an alloy with 10-volume-% SiC, and the other was made from an alloy with 20-volume-% SiC. The as-cast dimensions of each cylinder were 48 inches long, 10 inches inside diameter (ID), 12 inches outside diameter (OD).

Centrifugal casting of the MMC alloy resulted in the SiC particles segregating to the cylinder's outside surface with a resultant unreinforced metal inner layer. The volume fraction of particulate was found to increase across the reinforced layer; the maximum being near the outside shell surface. The particulate volume fraction of each casting, as measured across the reinforced layer, is shown in figure 1 (Glad, 1992). The mean volume-% of SiC particulate in the reinforced layers was 38% for the cylinder that was cast from the 20-volume-% SiC alloy, versus 30% for the cylinder that was cast from the 10-volume-% SiC alloy.

TESTING

Specimens were removed from a 3-inch x 6-inch block sectioned from the wall of each casting. The blocks were concurrently heat treated to the T6 condition prior to specimen machining. The heat treatment (figures 2 and 3) consisted of solution treatment at 1005 ±5°F in air for 12 hours; quench in water at 150°F; and age at 310 ±5°F in air for 4 hours.

Specimens were machined from the approximate center of the reinforced outer layer oriented in the axial direction of the cast cylinders. Specimen geometries are given in figure 4. The specimens were turned with single-point diamond tooling.

Electric resistive strain gages were installed on the specimens to measure both the axial and transverse strains during testing. All specimens were tested at 0.05 inch/minute.

TENSILE RESULTS

Results for tensile tests on three specimens of the 20-volume-% SiC alloy are plotted in figures 5, 6, and 7. Plotted for each specimen are *stress versus strain*, *stress versus tangent modulus* (read off the upper axis), and *Poisson's ratio* (read off the right

axis) *versus strain*. The material has a low ductility, breaking before it achieves a 0.2% offset yield strength. These plots also show that the material has a very low proportional limit. For example, it is seen in figure 5 that although the material starts out with a relatively high modulus near 22 Mpsi, its modulus rapidly falls off to 16 Mpsi at a stress level of 30 ksi and approximately 10 Mpsi at 40 ksi.

Results from three tensile specimens taken from the 10-volume-% SiC alloy are plotted in figures 8, 9, and 10. The ductility of this material is greater than and its stiffness is less than the 20-volume-% material, both properties being directly related to the amount of particulate reinforcement in the material.

Specimen 4T (figure 8) was cycled prior to the break to determine the material's strain-hardening behavior. The strain-hardening behavior was further explored in compression for both alloys.

Tensile results are tabulated in table 1.

Table 1. Tensile results.

Alloy	Specimen #	Yield Stress†	Breaking Stress	Total* Elongation
20-volume-% SiC	1T	^	50.9 ksi	0.40%
	2T	^	53.7 ksi	0.44%
	3T	^	49.2 ksi	0.32%
10-volume-% SiC	4T	47.2 ksi	53.1 ksi	0.82%
	5T	47.0 ksi	53.5 ksi	0.89%
	6T	46.2 ksi	52.6 ksi	0.85%

†0.2% offset
*both plastic & elastic
^specimen broke before attaining 0.2% offset

COMPRESSION RESULTS

Compression test results are plotted in figures 11, 12, and 13 for the 20-volume-% SiC alloy, and in figures 14 and 15 for the 10-volume-% alloy. The average yield stress (measured at 0.2% offset) for the three specimens of higher SiC particle content is 58 ksi. Strain hardening the material by approximately 1% compressive strain increased the yield stress to 81 ksi (averaged over two specimens), a 40% improvement. The average yield stress for the two specimens of lower SiC particle content is 51 ksi. Strain hardening one of these specimens to approximately 1.1% compressive strain increased its yield strength to 68 ksi, a 33% improvement.

Compression results are tabulated in table 2.

Table 2. Compression results.

Alloy	Specimen #	Yield Stress† (before strain hardening)	Yield Stress† (after strain hardening)
20-volume-% SiC	1C 2C 3C	56.5 ksi 58.9 ksi 58.4 ksi	80.8 ksi 80.8 ksi ^
10-volume-% SiC	4C 5C	51.3 ksi 50.8 ksi	^ 68.3 ksi

†0.2 percent offset
^specimen was not strain hardened

STRAIN HARDENING

Compressively strain hardening the centrifugally cast material by only 1% dramatically improved the material's compressive yield strength. The material's proportional limit was significantly increased as well. This was Vu's (1982) primary objective when he originally looked at hydrostatically strain hardening underwater pressure hulls made from discontinuously reinforced metal matrix composites. At that time, the material under investigation was the relatively expensive SiC whisker-reinforced aluminum made by powder metallurgy processing techniques. Cylinders were back extruded from consolidated billets. The composite contained 20-volume-% whiskers in a wrought 6061 aluminum alloy heat treated to the T6 condition. The compressive stress/strain behavior for that material, both before and after strain hardening, is plotted in figure 16. (The "strain-hardened" plot was "rezeroed," offsetting it by the amount of the material's permanent set [i.e., residual strain from compressively straining it 1.25%] to begin the plot at zero strain.) Because a significant degradation in the modulus of the material occurs prior to reaching its useable design stress (typically 0.2% offset yield strength), Vu's (1982) objective was to increase the material's modulus at working stress levels to improve the buckling resistance of pressure hulls.

Figure 17 compares the stress/strain behavior of the whisker-reinforced powder metallurgy material between the two centrifugally cast materials before strain hardening. (Plots for the 20- and 10-volume-% centrifugally cast specimens are respectively taken from Specimen 2C, figure 12, and Specimen 5C, figure 15.) In the nonstrain-hardened state, the centrifugally cast 10-volume-% material has compressive stress/strain behavior comparable to the much more expensive whisker-reinforced material.

The centrifugally cast materials, however, take much better advantage of strain hardening. This is deduced from figure 18 where the stress/strain behavior of all three

materials after strain hardening is compared. Centrifugally cast 20-volume-% SiC in the strain-hardened state has an impressive tangent modulus, exceeding 20 Mpsi up to a stress level of 60 ksi, and exceeding 18 Mpsi up to a stress level of 70 ksi.

OBSERVED INCLUSIONS

Each of the tensile fracture surfaces had at least one prominent dark inclusion. It is believed that, for at least some of these specimens, fracture originated at the inclusions, thereby contributing to the material's low elongations.

These inclusions stood out as a black speck in the surrounding grey fracture surface, easily observable with the unaided eye. Magnified fractographs (figures 19 and 20) do not necessarily reveal this stark contrast very well because of the many and irregular shadows formed under side illumination. The inclusions are highlighted with an arrow in the fractographs to differentiate them from shadows.

A cursory analysis was conducted to determine the makeup of these inclusions. One of the inclusions was examined in a scanning electron microscope by using x-ray spectroscopy. The x-ray spectrum (figure 21) reveals the elements silicon and zirconium to be prominent. The silicon is suspected to be either that which precipitated from the aluminum alloy, or in combined form as silicon carbide, since the detection method is not amenable to detecting any adjoining carbon. The zirconium is unexpected, and could possibly be in the combined form of zirconium oxide.

Although these inclusions were not previously mentioned in the prior work of Glad (1992) and Gungor (1990), it is suspected they are strewn throughout the material, because at least one inclusion was observed on every fracture surface. The inclusions are suspected to be a remnant of raw material processing rather than in the centrifugal casting step per se, since there is no explainable source for them in the centrifugal casting process. Possibly a zirconia ceramic adhesive coating was used on the tooling that was used in the original mixing of the composite alloy.

CONCLUSIONS

Tensile specimens had very low elongations, typically less than 1% for the 10-volume-% alloy and less than 0.5% for the 20-volume-% alloy, although they did demonstrate some degree of plasticity. All tensile fracture surfaces had at least one prominent dark inclusion, suspected to be typical artifacts in the raw material. Also, the proportional limit of the materials, measured in both tension and compression, was quite low.

Unexpectedly, compressively strain hardening the cast MMC material by only 1% achieved impressive mechanical properties for an underwater hull material.

Compressively strain-hardened MMCs were demonstrated to attain a **compressive yield strength greater than 80 ksi**, a modulus **greater than 20 x 10^6 psi up to 60 ksi**, and **greater than 18 x 10^6 psi up to 70 ksi**.

RECOMMENDATIONS

Further investigation into the strain hardening of centrifugally cast cylinders for underwater hull materials should be pursued. A more detailed study of strain-hardened mechanical properties should be conducted to include an evaluation of the material's fracture toughness and possibly its fatigue characteristics.

The potential of achieving even higher yield strengths from centrifugally cast MMCs by using other aluminum alloys and/or with more densely packed reinforcement (through modification of casting parameters and/or by using a different particulate morphology) should be considered.

An improvement in the material's mechanical properties can be expected with the elimination or reduction of the inclusions that were observed on the tensile fracture surfaces. The source of these inclusions should be determined and, if possible, eliminated. This is presumed to be an action item for the raw material supplier (i.e., Dural Aluminum Composites Corporation).

REFERENCES

Glad, W. E. April 1992. "Metallagraphic Analysis of Centrifugally Cast SiC Composites," NRaD TR1499.

Gungor, M. N. December 1990. "Centrifugal Casting for Metal Matrix Composites for Naval Applications," Final Technical Report, NSWC Contract Number N60921-89-C-0217.

Vu, B. 19 October 1982. "MMC Technology Study of Strain Hardening; Summary of," Memo, Ser. No. 9322/114-82, Naval Ocean Systems Center.

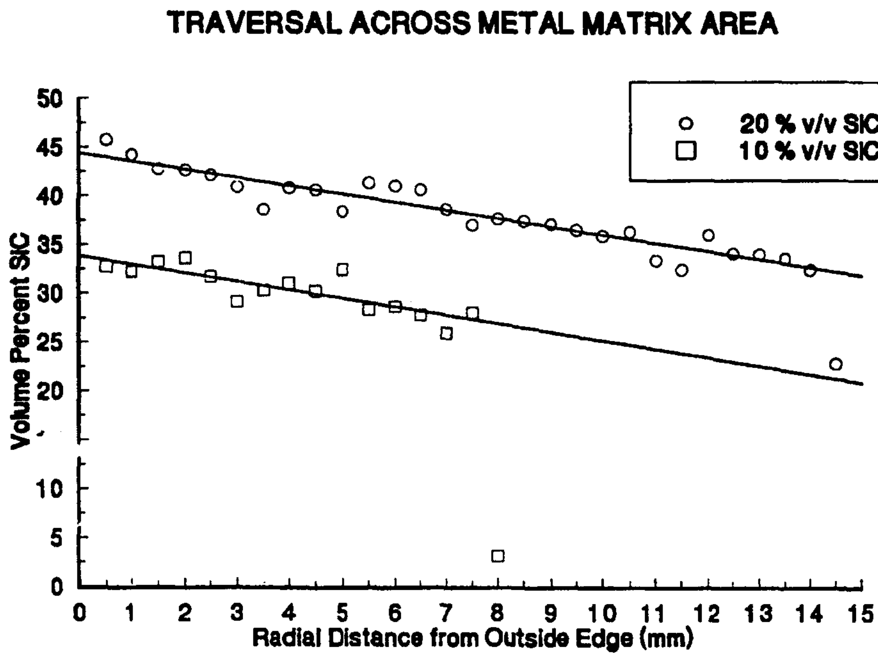

Figure 1. Quantitative digital image analysis measurements of SiC content in reinforced layer. Straight lines are linear least squares fit.

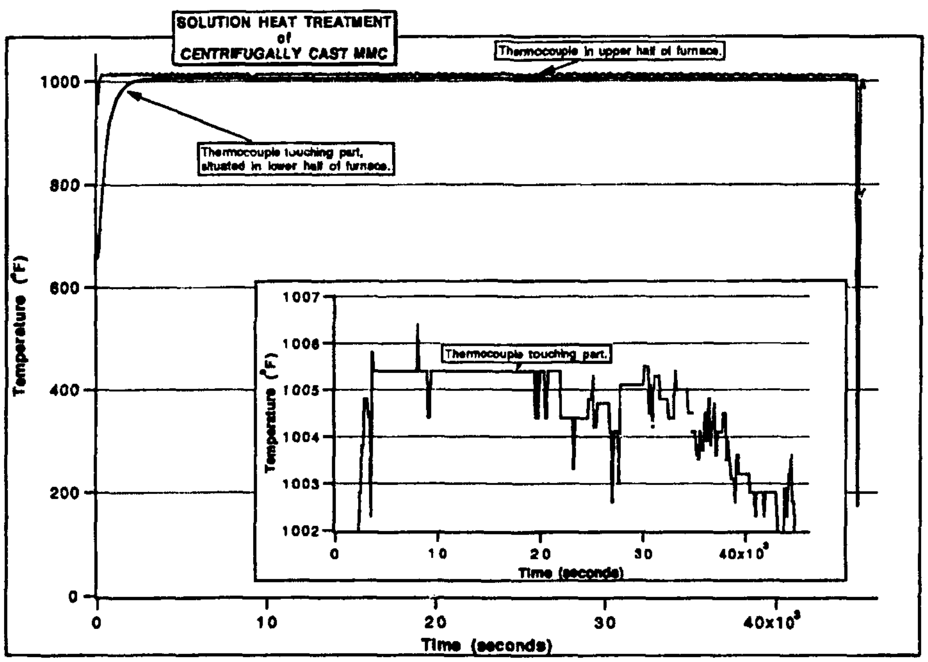

Figure 2. Solution heat treatment of centrifugally cast MMC. MMC components were placed in the furnace at time 0 seconds and removed at time 44,700 seconds.

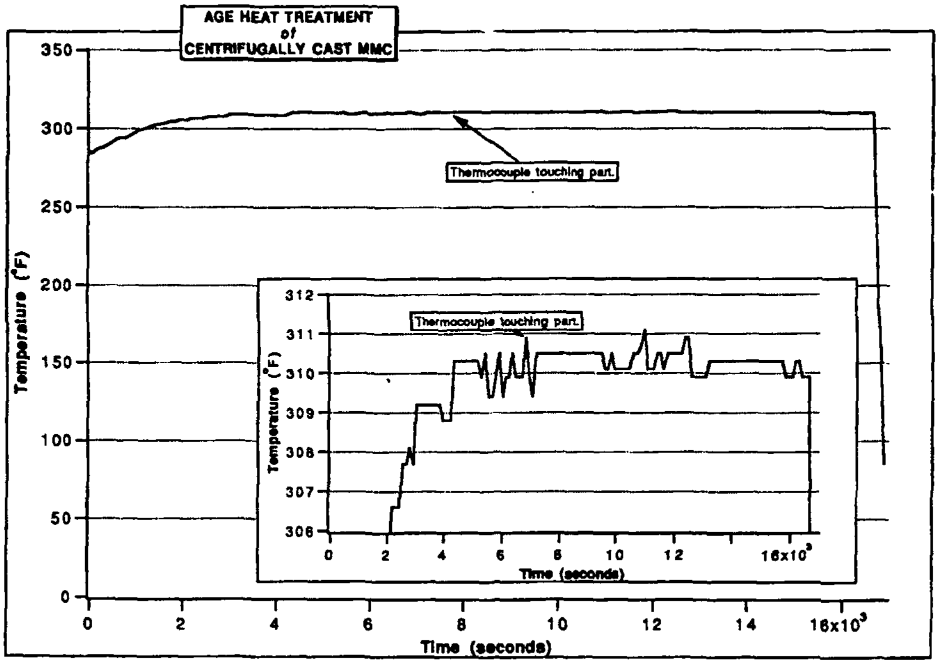

Figure 3. Artificially aging of centrifugally cast MMC. MMC components were placed in the furnace at time 0 seconds and removed at time 16,700 seconds.

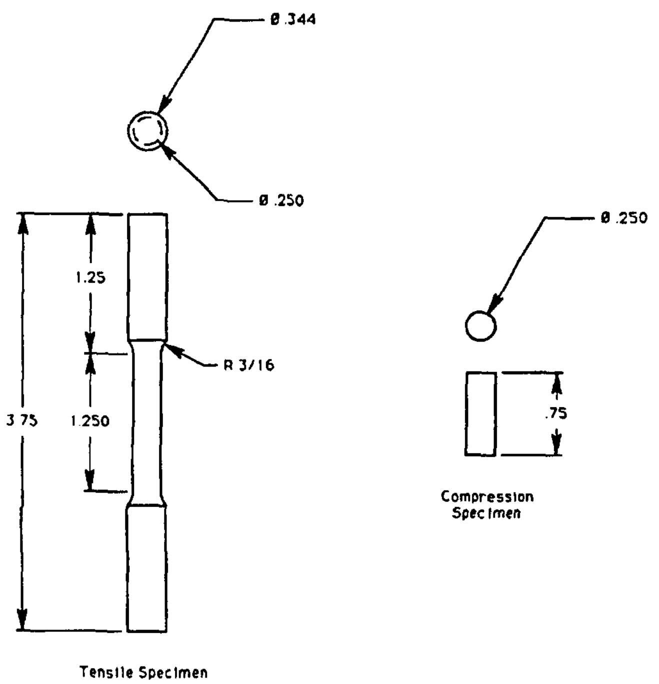

Figure 4. Dimensions of tensile and compression specimens.

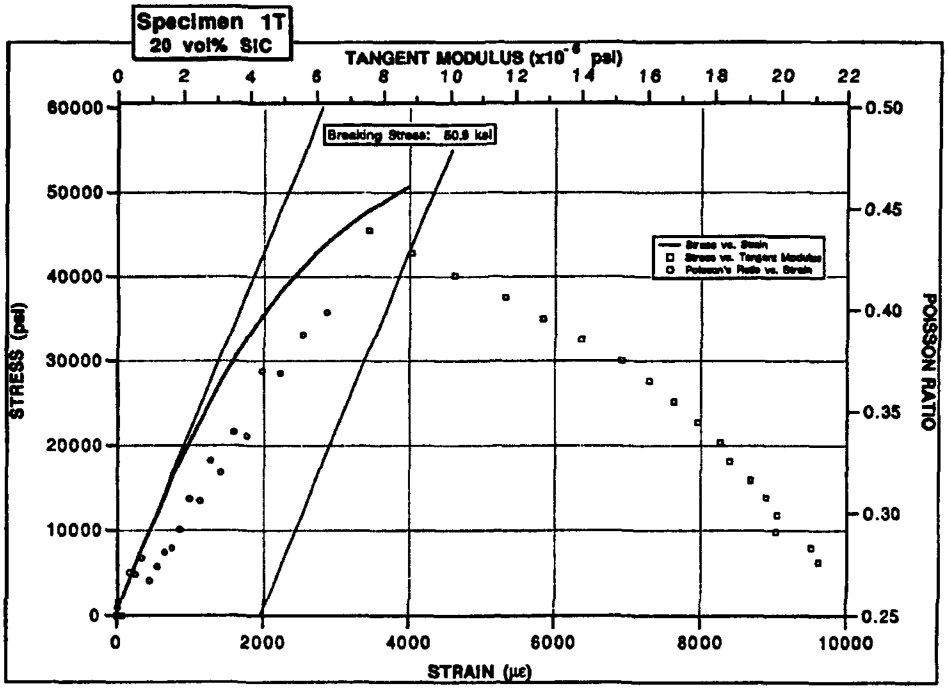

Figure 5. Tensile test of Specimen 1T, 20-volume-% SiC MMC.

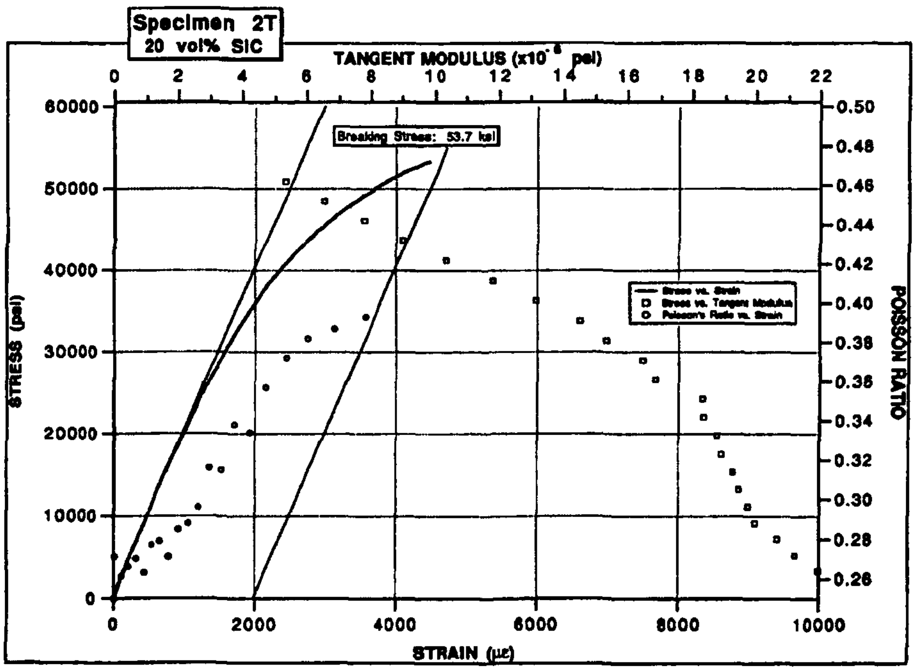

Figure 6. Tensile test of Specimen 2T, 20-volume-% SiC MMC.

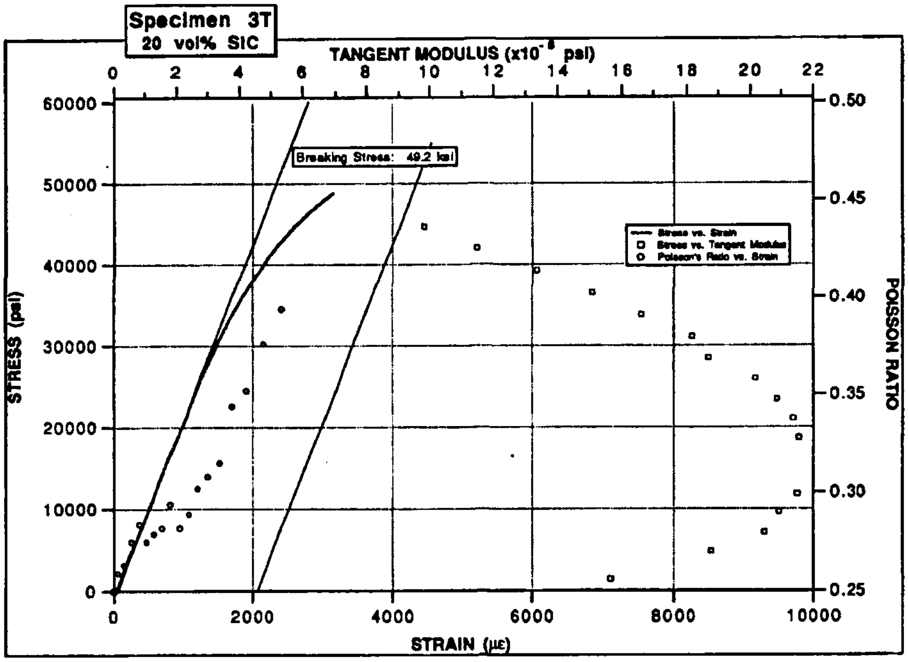

Figure 7. Tensile test of Specimen 3T, 20-volume-% SiC MMC.

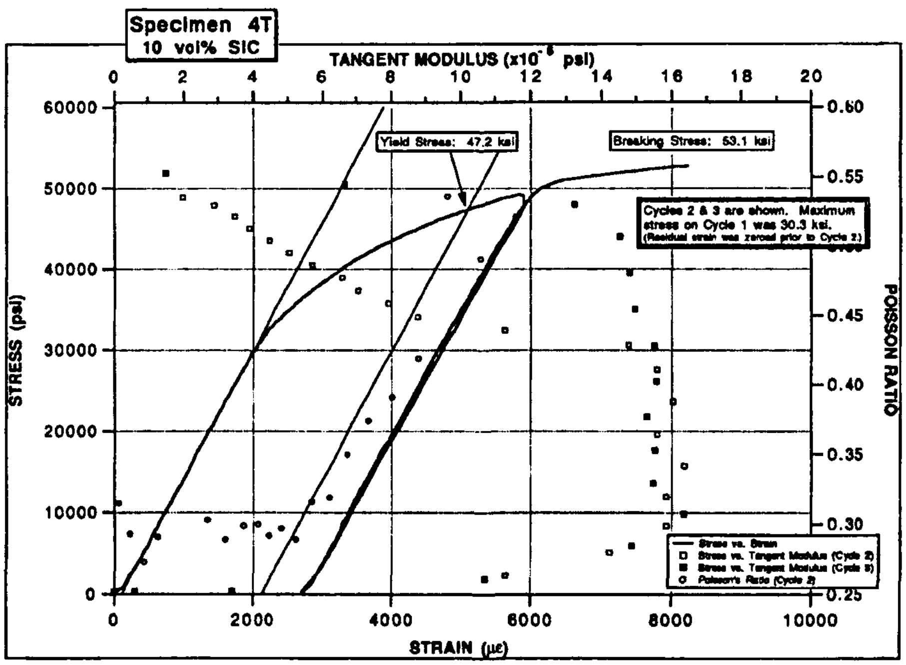

Figure 8. Tensile test of Specimen 4T, 10-volume-% SiC MMC.

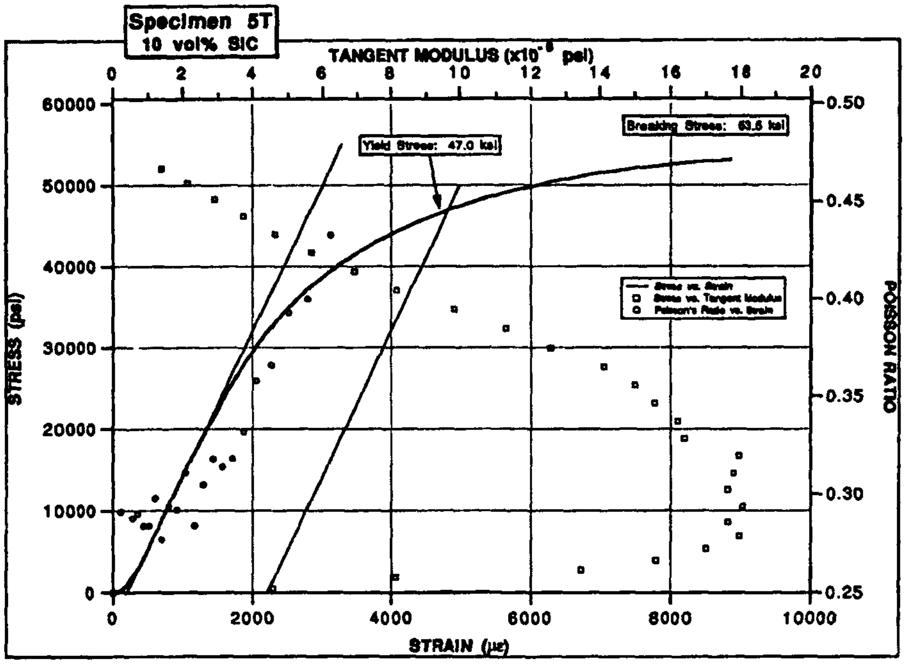

Figure 9. Tensile test of Specimen 5T, 10-volume-% SiC MMC.

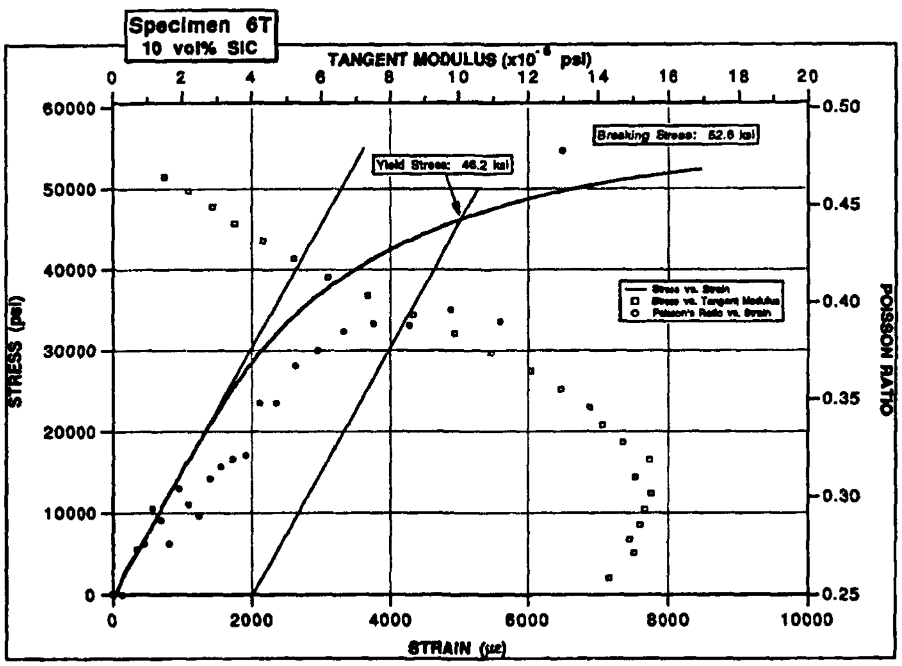

Figure 10. Tensile test of Specimen 6T, 10-volume-% SiC MMC.

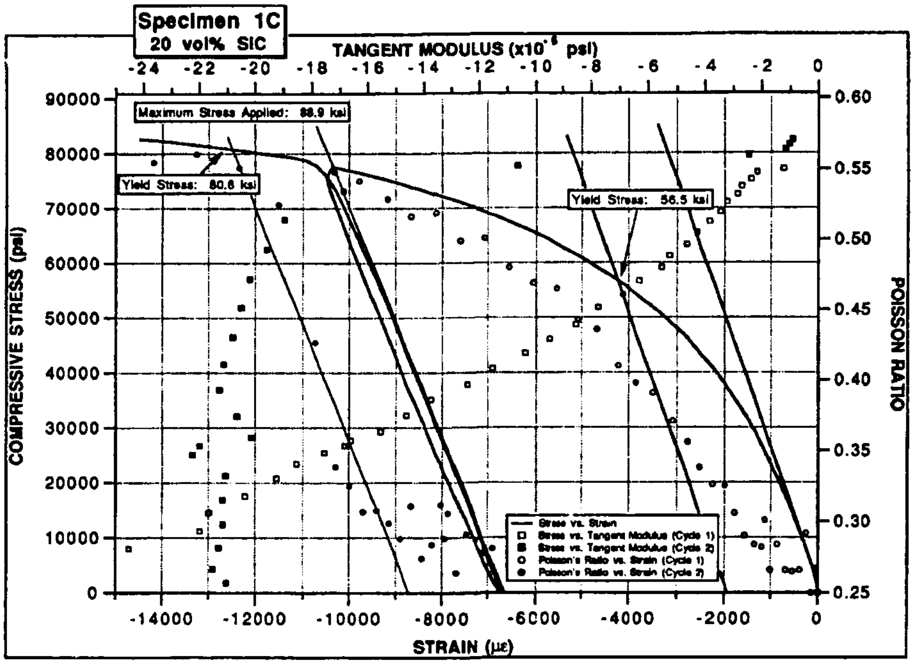

Figure 11. Compression test of Specimen 1C, 20-volume-% SiC MMC.

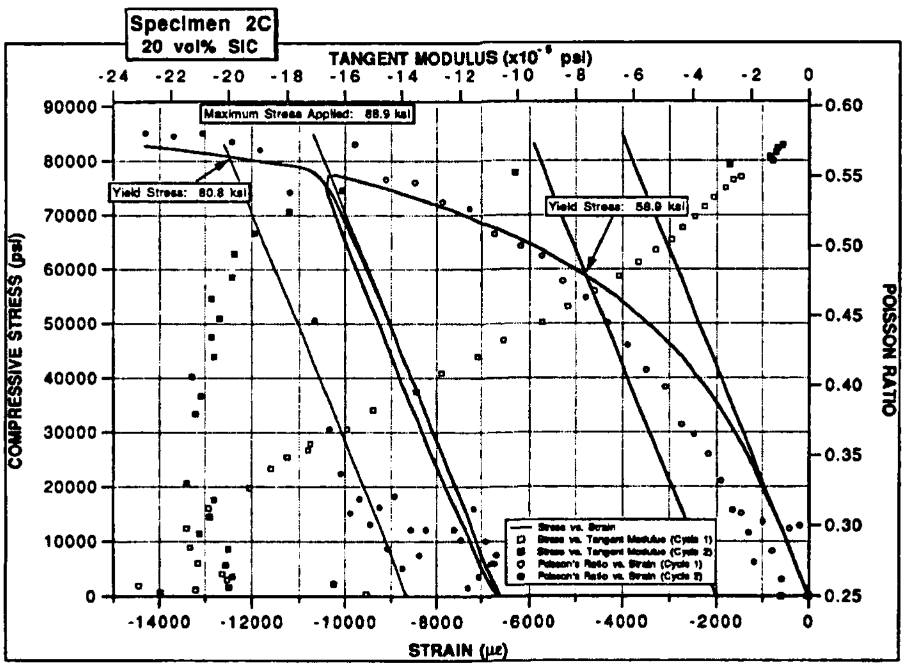

Figure 12. Compression test of Specimen 2C, 20-volume-% SiC MMC.

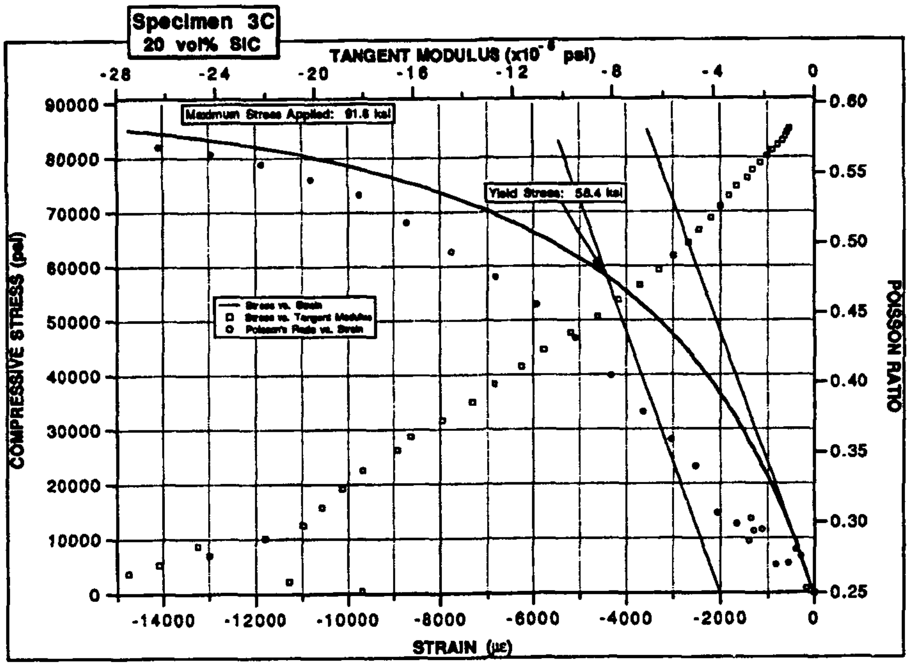

Figure 13. Compression test of Specimen 3C, 20-volume-% SiC MMC.

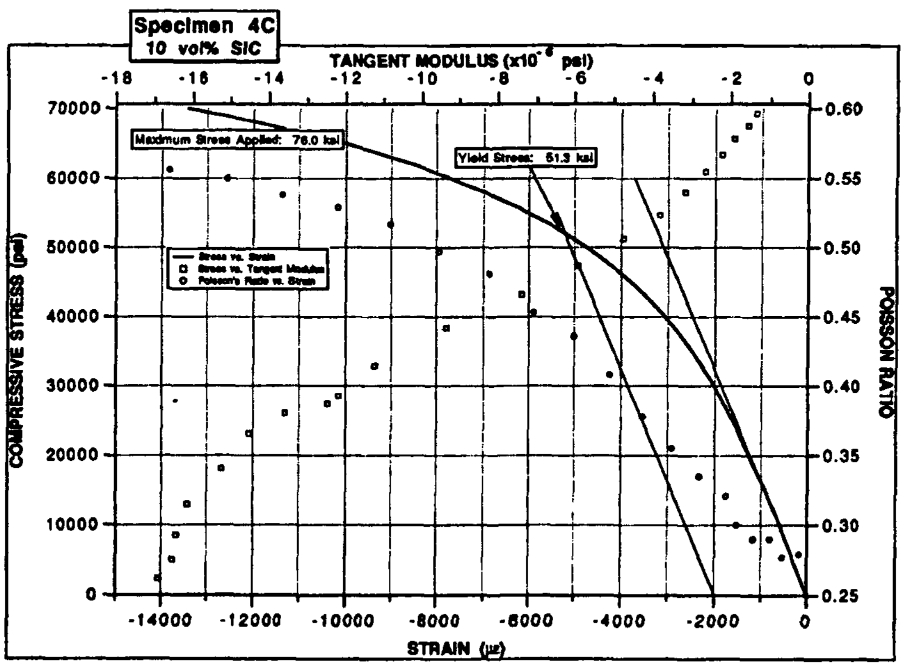

Figure 14. Compression test of Specimen 4C, 10-volume-% SiC MMC.

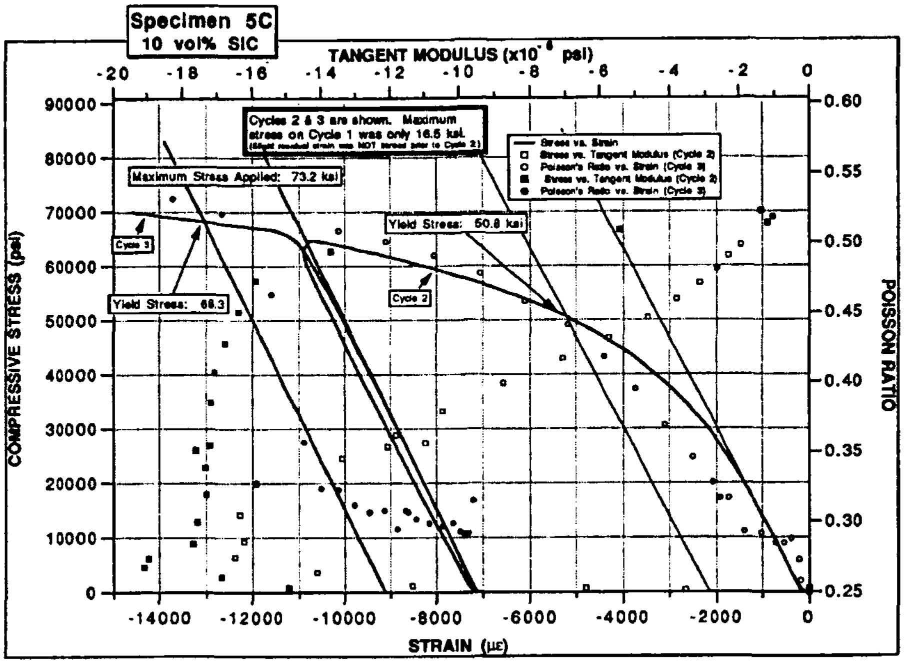

Figure 15. Compression test of Specimen 5C, 10-volume-% SiC MMC.

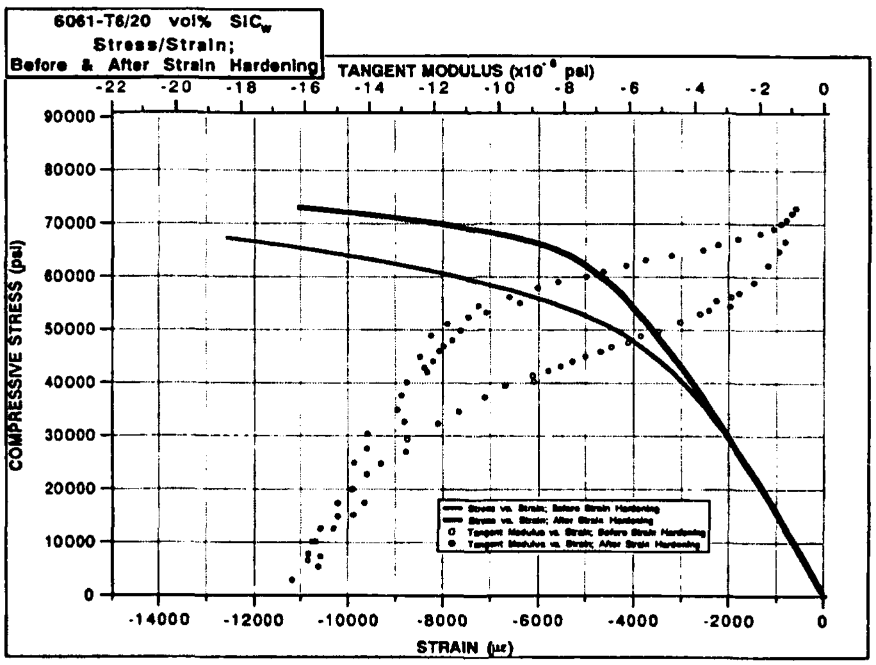

Figure 16. Stress/strain behavior of SiC whisker-reinforced 6061-T6 before and after strain hardening.

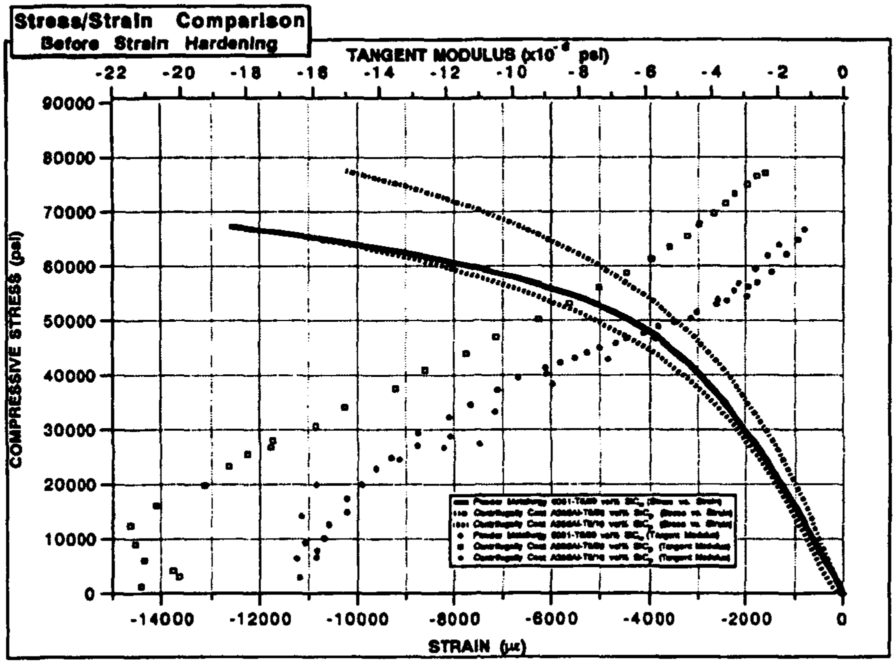

Figure 17. Comparison between the three alloys of their stress/ strain behavior before strain hardening.

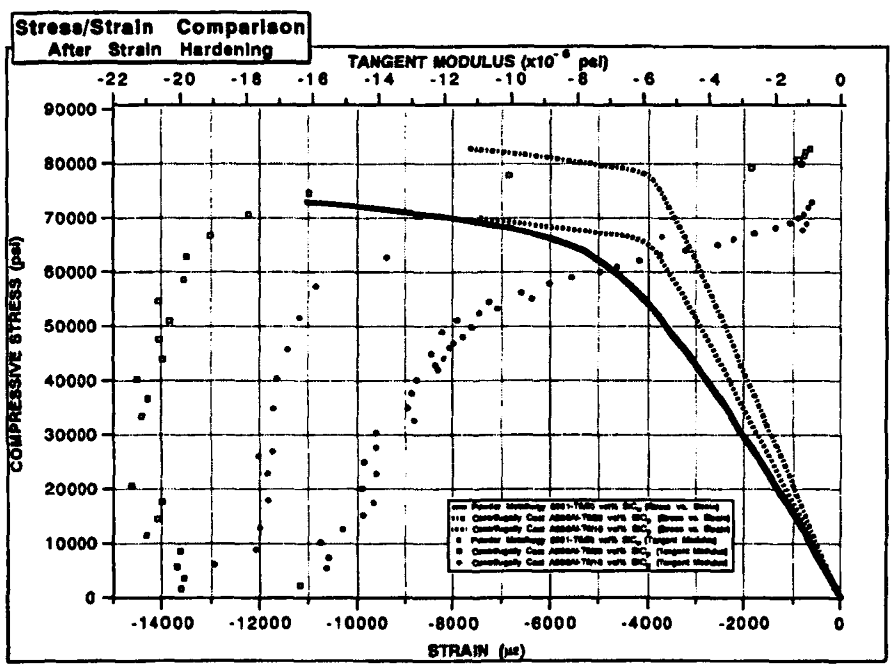

Figure 18. Comparison between the three alloys of their stress/ strain behavior after strain hardening.

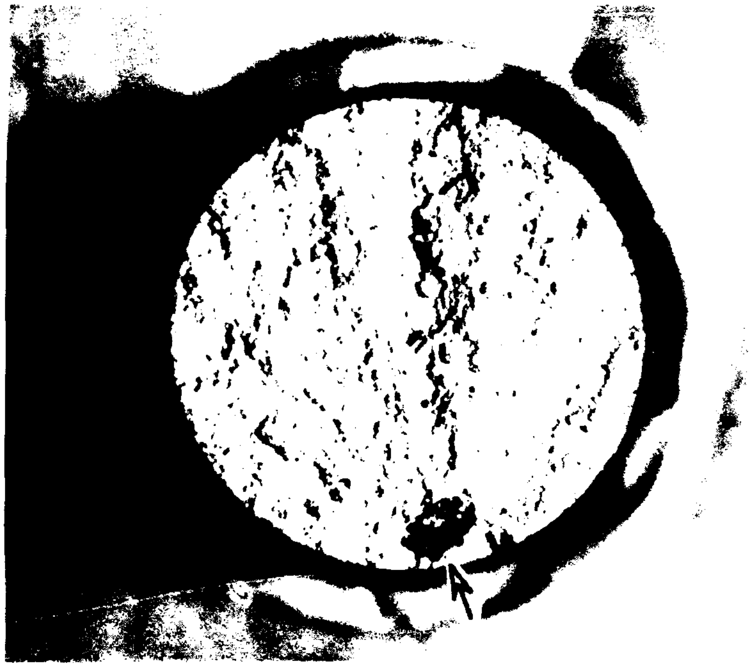

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Figure 19. Fracture surface of Specimen 3T. The inclusion is denoted with an arrow.

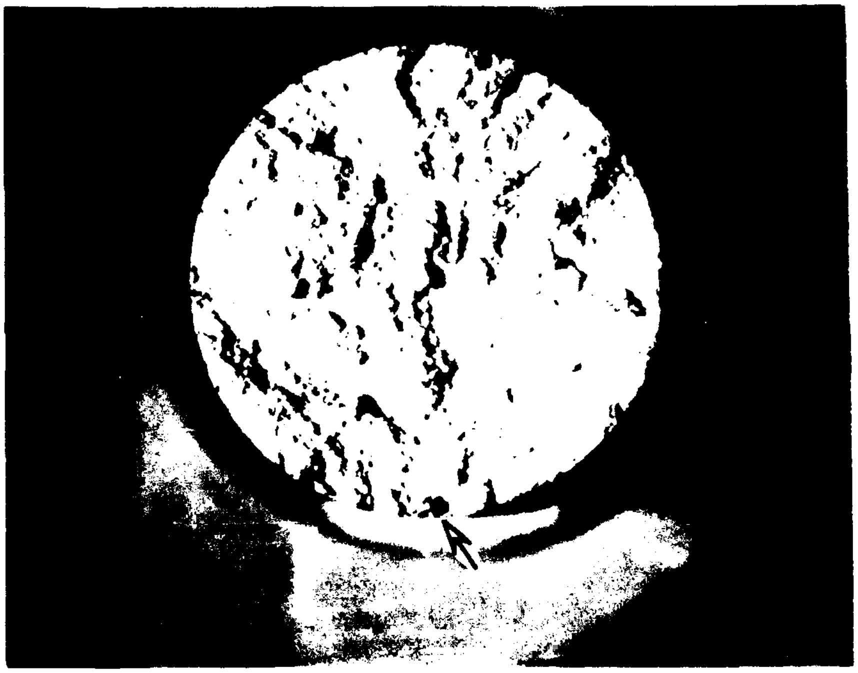

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Figure 20. Fracture surface of Specimen 4T. The inclusion is denoted with an arrow.

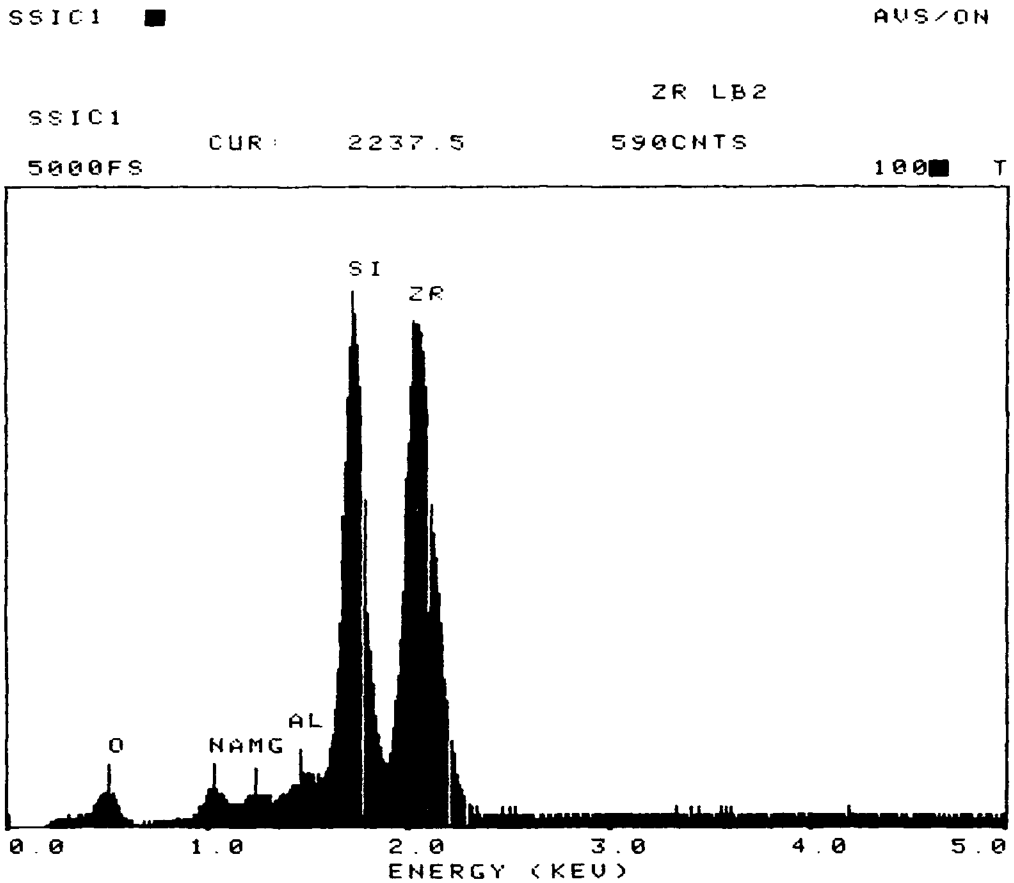

Figure 21. X-ray spectrum of one of the observed inclusions.

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The objective of this report was to determine the tensile and compressive mechanical properties for two metal matrix composite (MMC) aluminum cylinders manufactured by Westinghouse STC, Advanced Materials Department, through use of a centrifugal casting process.

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